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Prognosis of the steel aging of the pipe elbow in the Lithuanian Power Station

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1. Introduction

For transferring superheated steam from the turbine heat exchanger, the pipes are used which are currently undergoing long-term working temperature and mechanical stresses. Such pipeline performance depends not only from the load and from the temperature but also from the superheated water vapour content (aggressive hydrogen effect), diffusion processes in metals. Transferring technological parameters of superheated steam is very high: operating pressure in the pipe elbow Ø219 then the wall thickness changes in tensile zone from 28 and compression zone to 42 mm is 13.2 MPa. These pipe elbow are also affected by thermal stresses, by the weight of pipes elbow (including insulation), by the vibrations caused by the steam pressure variation and dynamic loads from the unbalanced pump rotor [1]. Working environmental parameters along the pipe elbow is the same. Pipe elbow during the manufacturing process is mechanically processed and at some regions the wall become thicker and at some regions become thinner. We modelled manufacturing process with spring back strains. Since this kind of strains is always due to residual strains. In such a state where residual stress-strain resides there is a big possibility to develop crack, since in the pipe working pressure rises residual stress value. In this work has been given a great attention to thick pipes elbow in which during the manufacturing process emerged residual stresses [2-4]. To simulate the process of pre stress-strain conditions the finite element method software LS-Dyna were employed. In this work the attention was focused on the working pipe elbow which operated only half of the potential work resource. There were determined all mechanical properties along the pipe elbows and by given data there were designed identical finite element model (FEM). The results obtained from finite element analysis (FEM) compared with the results obtained from the static tensile tests.

2. Methods of investigation of mechanical properties

In order to receive more precise mechanical properties from pipe elbow we made specimens from normal and tangential direction [5-7]. During the investigation of pipe elbow, there were tested 9 small specimens from the normal direction. Test was performed under the working temperature of 550°C and at this temperature were tested every 3 specimens. 16 small specimens taken from tangential direction were tested, at working temperature of 550°C. Hereafter specimens from tangential direction were divided into several zones: zones where tension stress takes plane - 9 peaces, neutral zone - 3 peaces, compression zone - 4 peaces. Main mechanical characteristics are reliable, because the results of scatter correspond statistical requirements. There were investigated the main mechanical properties: $\sigma_{pl.}$ - limit of proportionality, $R_{p0,2}$ - yield strength, R_m - ultimate strength, σ_f - stress at fracture, Z - reduction of cross-section area. In the Fig. 1 can be seen the scheme how the specimens were take from the pipe. In order to minimize thermal influence to the mechanical properties of the tensile test the specimens were cutted by high pressure water flow. Several plates (45×55×3 mm) were cutted from which afterall were subtracted two specimens with normal orientation and two specimens with tangential orientation. The scheme of specimens which were cutted from the pipe elbow and orientation of the small specimens in normal and tangential direction can be seen in Fig. 1.

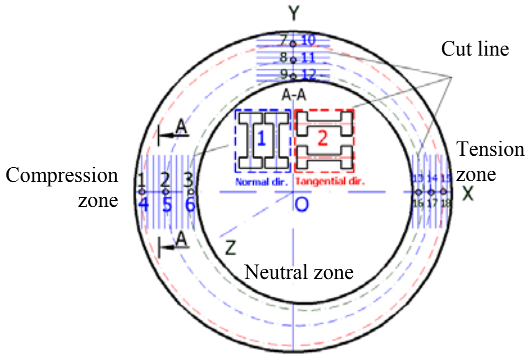

Fig. 1 The scheme of specimens which were cutted from the pipe elbow

The main dimensions of specimens are showed in the Fig. 2. Given small specimen were tested during static tensile test under the working temperature of 550°C (Figs. 3 and 4) [8-9].

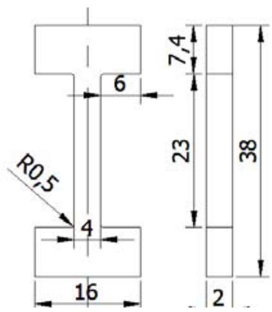

Fig. 2 Scheme the small specimens made from the steel 12Ch1MF

3. The results of the investigation of mechanical properties

In this work there were given the results from investigation of pipe elbow mechanical properties after the studies were performed with finite elements analysis. The investigation was performed under the working temperature of 550ºC [8, 9]. These mechanical prosperities were compared depending on the zones and direction. The tension strength curves are expressed taking into account real tension stresses, when the force is divided from the momentary cross-section area of the specimen (dotted lines), and taking into account so called engineering tension stresses, when the force is divided from in the initial cross-section area of the small specimen (continuous lines). One of the most important mechanical characteristics is the ultimate strength. In normal direction tensile zone ultimate strength is R_m = 230 MPa, it is the least value. This layer of pipe elbow is the most vulnerable at work time. In tangential direction, tensile zone R_m = 238 MPa. Second of main mechanical characteristics is the limit of proportionality. In normal direction, tensile zone, $\sigma_{pl..}$ = 142 MPa it is less than in tangential direction $\sigma_{pl..}$ =197 MPa. Data of pipe elbow (operating time is 45000 h), under working temperature of 550°C of mechanical characteristics from normal and tangential direction are given from the tensile, neutral and the compression zones are shown in Table 1 and 2. In Figs. 3 and 4 are tension curves from normal and tangential direction specimens. The data are given from the normal, neutral and the compression zones.

Table 1
Mechanical characteristics of normal direction specimens

Zones	Mechanical characteristics, MPa, %					
	$\sigma_{pl..}$	$R_{p0.2}$	R_m	σ_f	Z	A_5
Tensile	142	175	230	304	97.59	18.12
Neutral	174	199	239	317	97.93	17.66
Compression	196	215	250	292	95.22	17.03

Table 2
Mechanical characteristics of tangential direction specimens

Zones	Mechanical characteristics, MPa, %					
	$\sigma_{pl..}$	$R_{p0.2}$	R_m	σ_f	Z	A_5
Tensile	197	216	238	299	93.84	17.35
Neutral	182	202	240	317	96.89	17.69
Compression	189	225	250	334	95.98	17.50

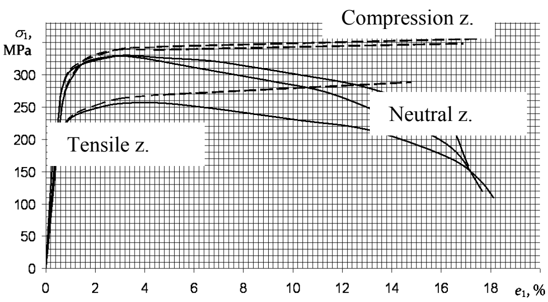

Fig. 3 Mechanical characteristics from normal direction

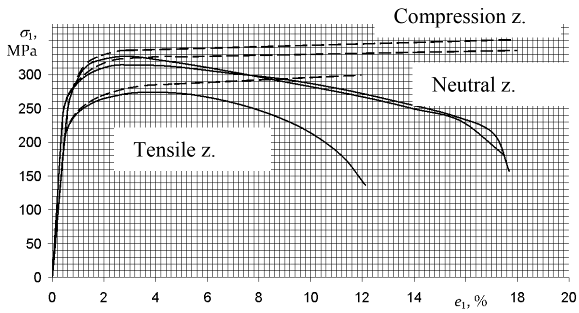

Fig. 4 Mechanical characteristics from tangential direction

According to dependences [10] we can prognosticate the main mechanical characteristics of pipe's elbow after $1{\cdot}10^4$ - $3{\cdot}10^4$ h of exploitation of T = 550°C. Mechanical characteristics using ageing dependence are shown in Table 3. Obtained application of the previously dependencies we can see aging of the materials evaluate.

Table 3
Mechanical characteristics using ageing dependence of the pipe elbow, operating time is $1{\cdot}10^4$ - $5{\cdot}10^4$ h, under working temperature of 550°C

Hours	Mechanical characteristics, MPa			
	$\sigma_{pl..}$	$R_{p0.2}$	R_m	σ_f
100000	121.10	165.87	232.87	286.47
200000	117.33	162.74	230.29	271.17
300000	115.13	160.91	228.78	262.22

4. Investigation of the strength of pipe elbow by the methods of finite element

In this work have been investigated stresses and strains of an elbow which worked at 550°C and was loaded with 13.2MPa inner pressure. An investigation has been conducted using two common methods: static tensile loading and modeling with Ls-Dyna software. Data from experiments was compared with results from finite element analysis. The pipe elbow Fig. 5 was modeled with three different boundary conditions: i.e. when the pipe is constructed from the separate tensile, compression and the neutral zones. Analysis was performed with mechanical properties from neutral and tangential zones. The second test has been investigated under the dynamical load conditions using FEA [11-13].

Fig. 5 Pipe elbow. Modelled with finite element consists of three zones: tension, neutral, and bended

Since the investigation concerns dynamic reaction in metal forming – the FEA was conducted using program for nonlinear dynamic analysis of structures in three dimensions ls971 single R4.2. To simulate investigated model we used a fully integrated 8 nodes-cubic element from LS-Dyna software elements range. This is three dimensional solid element in which elastic strain before yielding is finite. The type solid element and its formulation is specified though part ID (*PART) and the section ID (*SECTION_SOLID_OPTION). Chosen material model was *PIECEWISE_LINEAR_PLASTICITY. It is an isotropic elasto-plastic no. 24 material with arbitrary stress versus strain curve and arbitrary strain rate dependency can be defined. Failure based on a plastic strain or a minimum time step can be defined. If considering laminated or sandwich shells with non-uniform material prosperities, the material model *MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY is recommended.

Also, a local coordinate system for orthotropic and anisotropic materials can be defined by using the ORTHO option. If extra degrees of freedom are needed, the DOF option should be used. The option TET4TOTET10 should convert 4 nodded tetrahedrons to 10 nodded tetrahedrons.

The INERTIA option allows the internal properties and initial conditions to be defined rather than calculated from the finite element mesh. This applies to rigid bodies, with keyword *MATRIGID only. The REPOSITION option applies to deformable materials and is used to reposition deformable materials attached to rigid dummy components whose motion is controlled by either CAL3D or MADYMO. At the beginning of the calculation each component controlled by CAL3D/MADTMO input. However, deformable materials attached to these components will not be repositioned unless this option is used.

5. Investigation results of FEA

LS-Dyna modelling software introduces mechanical characteristics of each layer separately. There were also introduced data taken from normal and the tangential direction of the pipe.

In order to evaluate overloaded pipe elbow during starting up and ending up the steam dynamic loading case were evaluated. Pipe dynamic loading in time moment is given in the Fig. 6. Modelled pipe working pressure reaches 13.2 MPa.

After the initial analysis, results show that the weakest and the most dangerous place in the pipe elbow is stretched area in oriented normal direction. For more detailed assessment of the potential impact of dynamic load in the pipe elbow we continued to study the particular case.

After the examination of Lithuanian Power Company superheated steam pipe elbows which worked 45000 hours the following conclusion can be drawn. The pipe elbow was modelled with finite elements. The mechanical properties of materials at 550ºC were investigated.

Stress distribution the pipe elbow of normal direction D219x28.5 after 45000 h exploitations are shown in Table 4. Maximum compression of radial stress was in compression zone inner layer stresses is σ_R = -12.525 MPa. In the neutral zone middle layer σ_R stress is 2.6 times less than in inner layer compression zone. The maximum value of circumferential stress was in tensile zone inner layer stresses is σ_H = 31.793 MPa. In the neutral zone middle layer stress is 1.3 times less than in tensile zone inner layer. In tension zone outer layer the stresses is 1.2 times more than in the neutral zone middle layer.

Stresses σ_R in straight pipe [10] of normal direction of outer layer is 1.35 times less than in pipe elbow in neutral zone outer layer. Maximum stresses σ_H is in straight pipe inner layer, these stresses is 1.44 times more than in neutral zone inner layer of pipe elbow.

Stress distribution the pipe elbow of tangential direction after 45000 h exploitations are shown in Table 5. Maximum compression of radial stress was in compression zone inner layer stresses is σ_R = -12.076 MPa. In the neutral zone middle layer stress is 2.85 times more than in compression zone inner layer. In tension zone outer layer the stresses is 3.75 times more than in compression zone inner layer. The maximum value of circumferential stress was in tensile zone inner layer stresses is 1.29 times more than in neutral zone middle layer, and in tension zone outer layer the stresses is 1.17 times less than in neutral zone middle layer.

Stresses σ_R in straight pipe [10] of tangential direction of outer layer is 1.18 times less than in pipe elbow in neutral zone outer layer. Maximum stresses σ_H in straight pipe is in inner layer , these stresses is 1.90 times more than in neutral zone inner layer of pipe elbow. The results show that tension layer is most dangerous layer of pipe elbow.

Different of value of stresses between normal and tangential directions is about 8%.

Table 4
Stress distribution in the pipe D219x28.5 elbow for specimens orientated in normal direction
after 45000 h exploitations

Work time, h	Zone	Stresses	Stresses, MPa		
			Outer	Middle	Inner
45000	Tension	σ_R	-1.097	-4.752	-11.910
		σ_H	20.264	23.904	31.793
	Neutral	σ_R	-1.103	-4.737	-11.932
		σ_H	20.097	23.831	29.886
	Compression	σ_R	-1.031	-4.470	-12.525
		σ_H	17.313	22.306	30.093

Inflection in the normal direction in Table 6 of the tensile zone inner layer stresses is σ_{Misses} = 53.755 MPa. In the neutral layer middle zone middle layer stress is σ_{Misses} = 35.143 MPa and in tension zone outer layer the stresses is σ_{Misses} = 26.423 MPa.

Very similar results are obtained in the tangential direction in Table 7 of the tensile zone inner layer stresses is σ_{Misses}= 53.994 MPa.

Table 5
Stress distribution in the pipe D219x28.5 elbow for specimens orientated in tangential direction
after 45000 h exploitations

Work time, h	Zone	Stresses	Stresses, MPa		
			Outer	Middle	Inner
45000	Tension	σ_R	-1.129	-4.247	-12.848
		σ_H	20.469	24.982	30.989
	Neutral	σ_R	-1.525	-4.232	-12.971
		σ_H	20.099	24.008	30.084
	Compression	σ_R	-1.952	-4.159	-12.076
		σ_H	17.059	22.452	30.295

Table 6
Von Misses stresses distribution in the pipe elbow for specimens orientated in normal direction after 45000 h exploitations

Zone	Stresses, MPa		
	Outer	Middle	Inner
Tensile	26.423	35.258	53.755
Neutral	26.216	35.143	51.598
Compression	25.155	34.566	52.545

Table 7
Von Misses stresses distribution in the pipe elbow for specimens orientated in tangential direction after 45000 h exploitations

Zone	Stresses, MPa		
	Outer	Middle	Inner
Tensile	26.683	35.882	53.994
Neutral	26.946	34.834	53.135
Compression	25.592	34.514	52.364

In order to investigate the influence of the human factor to the possibility of the accident we loaded the pipe elbow with the dynamical load. That‘s how it will be simulated quick opening of the overheated steam pipe valve. Dynamic loading case revealed that more than 95% of the work load pressure reaches its value in less than 1% of over all loading time. Such a load in the pipe elbow is caused by resonant simulation processes [14 - 16]. Tension drops across the layer to normal direction to 64.696 MPa. That pipe bending admissible stress is $\sigma_{adm.}$ = 66 MPa. We see that the dynamic loading of saturated steam pipe elbow has almost reached this level. The results stress distribution in time of tangential direction, tension zone presented in Fig. 6, and the stress distribution in space of presentation in Fig. 7.

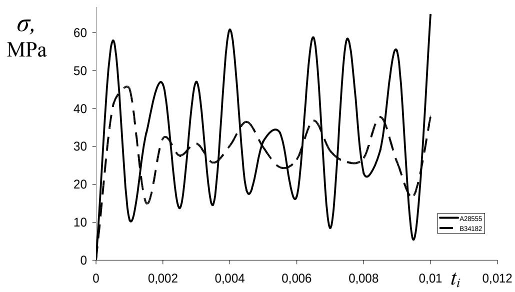

Fig. 6 Tension layer of tangential direction of two different places of pipe elbow internal stress distribution in time

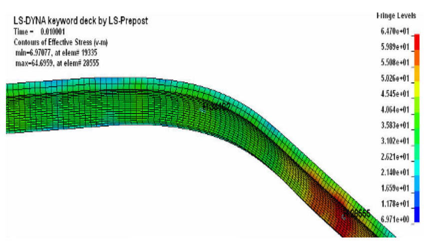

Fig. 7 Tension layer of normal direction of pipe elbow internal stress distribution in space

We can see the influence of the human factor is very high. Because the stress in the tensile zone of the pipe two times as higher as then the stress at the normal working conditions.

6. Conclusions

One of the most important mechanical characteristics is the ultimat limit - R_m. Strength limit of normal direction small specimens changes from 230 to 250 MPa. The ultimate limit of tangential direction small specimens changes from 238 to 250 MPa.

Using FEA methods by Ls-Dyna was calculated stress strain von Misses in 45000 h worked pipe. Minimum value of radial stress was of normal direction in compression zone inner layer stresses is σ_R = -12.525 MPa, The maximum value of circumferential stress was in tensile zone inner layer stresses is σ_H = 31.793 MPa.In the normal direction of the tensile zone inner layer stresses is σ_{Misses} = = 53.755 MPa. In the neutral layer middle zone middle layer stress is σ_{Misses} = 35.143 MPa. In middle of tension zone Von Misses maximal stresses was σ_{Misses} = = 67.967 MPa, then value of $\sigma_{adm.}$ = 66 MPa. The results show that tension layer is most dangerous layer of pipe elbow.

Dynamic loading case revealed that more than 95% of the work load pressure reaches its value in less than 1% of over all loading time. Such a load in the pipe elbow is caused by resonant simulation processes. Elbows are exposed to sudden impact loading. Tension drops across the layer to normal direction to 64.696 MPa. That pipe bending admissible stress is $\sigma_{adm.}$ = 66 MPa. We see that the dynamic loading of saturated steam pipe elbow has almost reached this level.

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VAMZDŽIO ALKŪNĖS DARBO RESURSO PROGNOZAVIMAS LIETUVOS ELEKTRINĖJE

R e z i u m ė

Šiame straipsnyje pateikta vamzdžio lenktosios dalies mechaninių charakteristikų tyrimas baigtinių elementų metodu, esant 550ºC eksploatacijos temperatūrai. Vamzdžio alkūnės modelis buvo sumodeliuotas esant trims skirtingoms kraštinėms sąlygoms, t. y. kai vamzdis yra sudarytas iš atskirų tempimo, gniuždymo bei neutraliosios zonų tiek normaline, tiek tangentine kryptimis, taip pat dinaminio apkrovimo atveju.

Atlikus AB Lietuvos elektrinės perkaitintojo garo perdavimo vamzdžio alkūnės, eksploatuotos 45 000 valandų, medžiagų mechaninių charakteristikų tyrimus darbinėje 550ºC temperatūroje baigtinių elementų metodu, galima pasakyti, kad įtempiai neviršija leistinųjų.

Dinaminio apkrovimo pobūdis dinamiškas – daugiau nei 95% darbinės slėgio apkrovos pasiekia savo vertę mažiau nei per 1% apkrovai skirto laiko. Toks vamzdžio apkrovimo imitavimas sukelia alkūnėje rezonansinius procesus. Tempiamo sluoksnio normalinės kryties elemento įtempiai dukart didesni nei paprasto apkrovimo atveju. Taigi dinamiškai apkrauta persotintojo garo vamzdžio alkūnė dirba labai pavojingu režimu.

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PROGNOSIS OF THE AGING OF THE PIPE ELBOW IN THE LITHUANIAN POWER STATION

S u m m a r y

In this paper there were given the results from the investigation of the mechanical properties of pipe elbow modeled with finite element under the working conditions of 550ºC. The pipe elbow was modeled with three different boundary conditions: i.e. when the pipe is constructed from the separate tensile, compression and the neutral zones. Analysis was performed with mechanical properties from neutral and tangential zones. The second test has been investigated under the dynamical load conditions.

After the investigation of mechanical properties of overheated steam pipe elbow under the working performance of 45000 exploitation time at AB Lithuania power plant and under the working temperature of 550ºC there can be draw a conclusion that stress do not exceed the admissible stress limit.

At the dynamical load case, more then 95% of working pressure reaches its load limit in less then the 1% of total intended time. Such an imitation of the load causes resonance processes.

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